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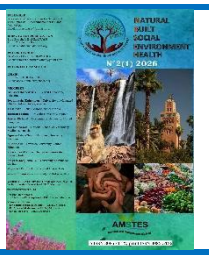

Microalgae-Based Bioremediation of Microplastic-Contaminated Industrial Wastewater: Mechanisms and Challenges

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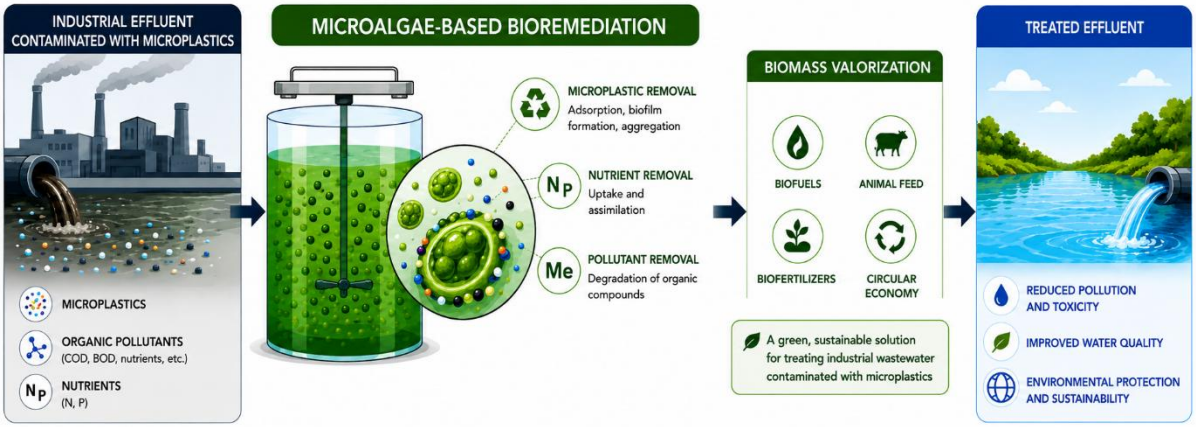
Graphical Abstract

The integration of microalgae into various industrial wastewater treatment systems is an environment-friendly bioremediation strategy against both organic pollution and microplastic contamination. Following treatment, the resulting biomass offers multiple opportunities for valorization, particularly in the production of biofuels, biofertilizers, and animal feed. Their use fits perfectly within a sustainable and circular economy approach.



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Abstract: Microalgae-based bioremediation presents a promising eco-friendly approach for removing microplastics (MPs) from industrial effluents. This review summarizes the current understanding on this subject. The article begins by describing the characteristics and origins of MPs in industrial discharges. It then reviews documented mechanisms of microalgae–MP interactions, including adsorption/biosorption, bioflocculation, accumulation, and partial degradation. Important environmental and operational factors that influence treatment efficiency—such as MP size and charge, algal species, and culture conditions—are analysed. Additionally, the article discusses analytical methods necessary for MP characterization and monitoring performance. Microalgae-based methods are contrasted with traditional physical and chemical processes, highlighting the potential value of the processed biomass (such as bioenergy and biofertilizers) to showcase a circular bioeconomy approach. The review concludes by pinpointing key research gaps and offering recommendations for standardizing experimental procedures and encouraging the adoption of microalgal systems within sustainable wastewater treatment strategies.

Keywords: *Microplastic removal, Microalgae, Wastewater treatment, Biodegradation.*

Introduction

Among the major environmental problems of the twenty-first century is microplastic pollution. Most of these particles reach aquatic ecosystems through industrial effluents [1]. Conventional wastewater treatment technologies, such as coagulation, filtration, and biological processes, do not show very effective results in removing small particles measuring less than ten micrometres [2]. Moreover, they often produce secondary sludge, the treatment of which is very costly. Because of these limitations, it has become essential to look for other solutions that are more effective, more sustainable, and more cost-effective.

Among the emerging solutions, the use of microalgae-based systems is attracting growing interest because of their multifunctional role in wastewater treatment. Microalgae can interact with microplastics through physico-chemical adsorption on the cell surface, as well as on extracellular polymeric substances (EPS), promoting bioflocculation, which potentially contributes to the partial degradation of the polymers [1].

At the same time, microalgae make it possible to recover nutrients and produce biomass. This helps create treatment strategies based on the circular economy [2]. But, their large-scale use, such as at the industrial scale, remains limited for several reasons, such as the toxicity caused by microplastics, the time required for treatment, and the difficulty of separating microalgae–microplastic aggregates in order to valorize them afterwards [3,4].

Microplastics are plastic particles measuring less than five millimetres that come from two distinct types of sources. First, primary sources, such as microbeads and synthetic fibres; or secondary degradation of larger-sized plastics [5]. They present different morphologies and can appear in the environment in the form of fibres, fragments, films, or spheres, etc. They are composed of several polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) [6,7] (Fig. 1). Their environmental behaviour depends largely on their physicochemical properties, such as size, density, and surface charge. These properties also influence the way they interact with microalgal cells [8,9]. This is the reason why these characteristics are very important for improving biological treatment strategies [10].

Industrial effluents are an important source of microplastics in water, especially those coming from the textile, plastic, cosmetics, pharmaceutical, and food-processing industries [11]. During certain operations, such as synthetic fibre washing, plastic manufacturing, or cosmetic

formulation, microplastics are released into wastewater [12]. During certain operations, such as synthetic fibre washing, plastic manufacturing, or cosmetic formulation, microplastics are released into wastewater [13].

In addition to their presence in the environment, microplastics have important effects on microalgae, these essential organisms in natural and engineered aquatic environments [14,15]. Being exposed to microplastics can cause oxidative stress, reduce the efficiency of photosynthesis, and also affect the growth of microalgae [16]. Moreover, when microplastics and microalgae interact with each other, this can change the aggregation and sedimentation processes, as well as the nutrient cycle in aquatic ecosystems [17]. It is thus very important to understand the interactions between these small particles and these microorganisms, with the aim of improving the biological treatment of wastewater and making it more effective under real industrial conditions [15].

Figure 1. Major plastic polymers and their common applications contributing to microplastic pollution.

Microalgae-Based Bioremediation: Concept and Mechanisms

General Concept of Microalgal Bioremediation

The application of microalgae for bioremediation has gained attention as a sustainable and green strategy for treating industrial effluents polluted with microplastics. Microalgae are able to remove pollutants while producing biomass that can be valorized for bioenergy, biofertilizers, or bioproducts [18]. This double function makes them particularly interesting for integrated circular wastewater treatment systems. Moreover, microalgae represent a biological platform for the capture of microplastics through physicochemical interactions and aggregation, which could potentially reduce the concentration of MPs in the treated waters below the levels expected by conventional methods.

Mechanisms of Interaction Between Microalgae and Microplastics

Microalgae interact with microplastics through multiple mechanisms:

Adsorption/Biosorption: Microplastics adsorb on the surface of algal cells or extracellular polymeric substances (EPS) to form stable aggregates. The EPS secreted by the algae enhances the ability to bind with various types of polymers [19].

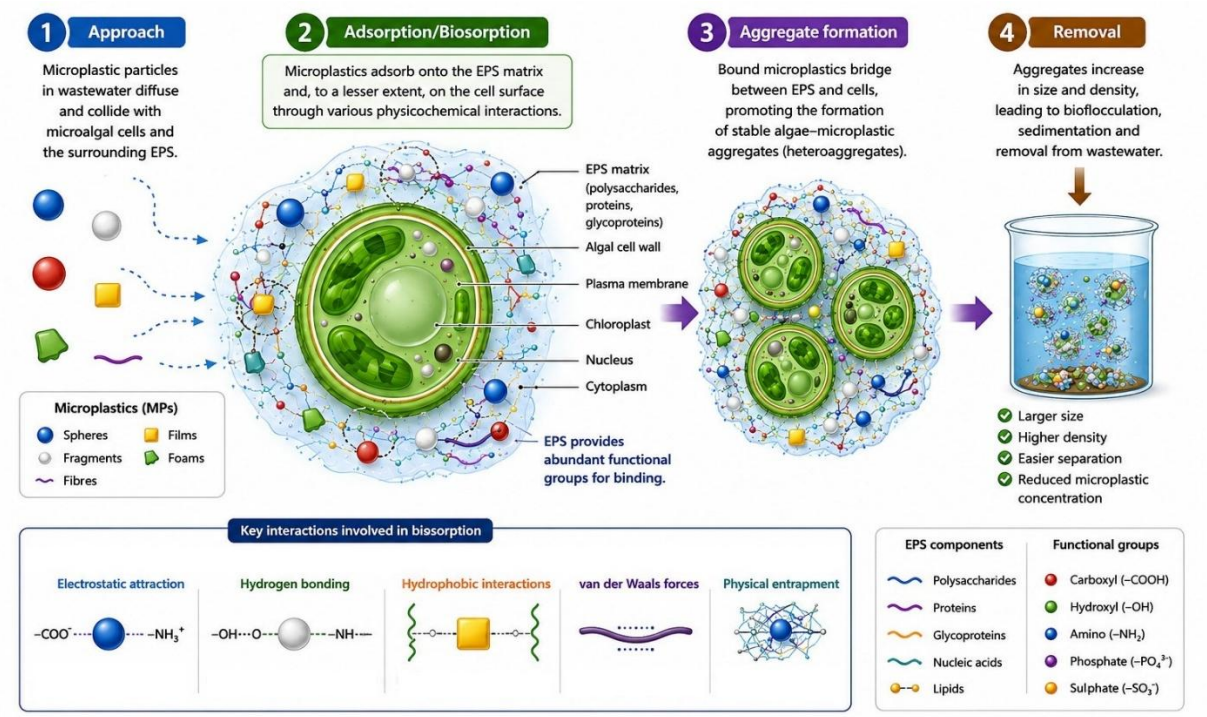

Figure 2. Schematic representation of microplastic adsorption/biosorption by microalgae and subsequent bioflocculation-mediated removal.

Bioflocculation: microplastics adhere to algal cells, promoting sedimentation and removal from the aqueous phase. The efficiency of bioflocculation depends on the algal species, the type of microplastics and environmental conditions [19,20] (Fig. 3).

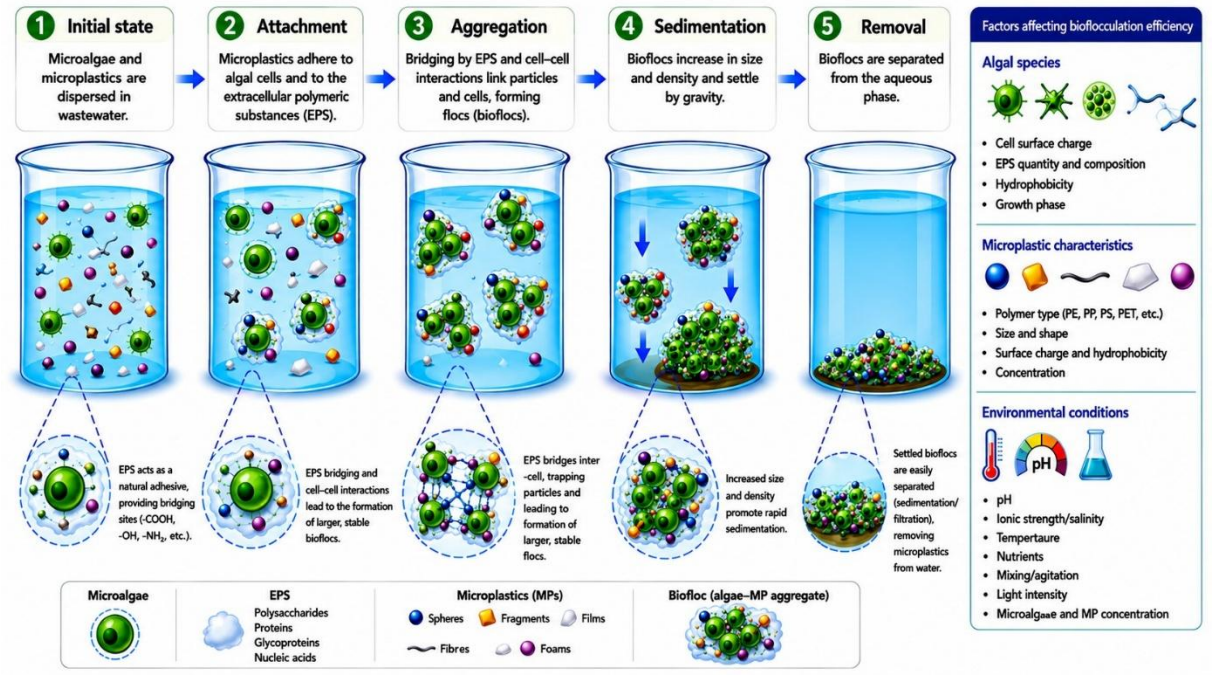

Figure 3. Schematic representation of EPS-mediated bioflocculation, sedimentation, and removal of microplastics by microalgae.

Bioaccumulation and Partial Biodegradation: ingestion of small microplastics and their partial degradation through enzymatic or oxidative processes. Polymers are only degraded to a limited extent, and these interactions contribute to reducing their persistence in the environment [21,22] (Fig. 4).

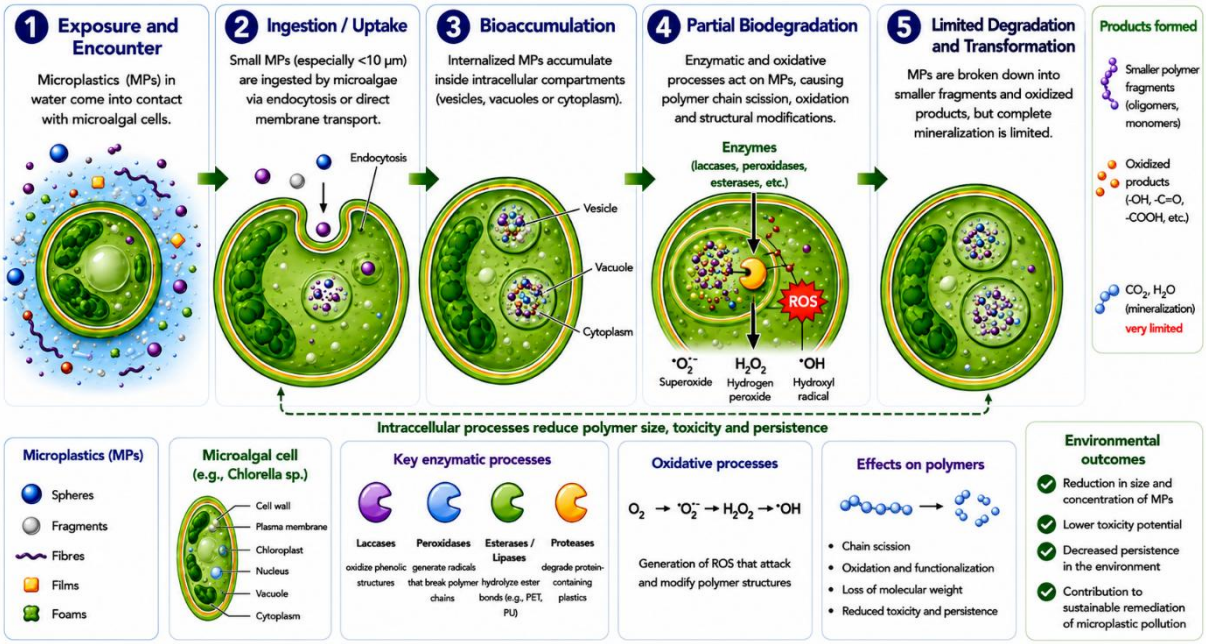

Figure 4. Schematic representation of microplastic bioaccumulation, partial biodegradation, and transformation by microalgae.

Photobiological Effects: Photosynthesis in microalgae can lead to the oxidative transformation of adsorbed microparticles and thus further contribute to bioremediation [19,23] (Fig. 5).

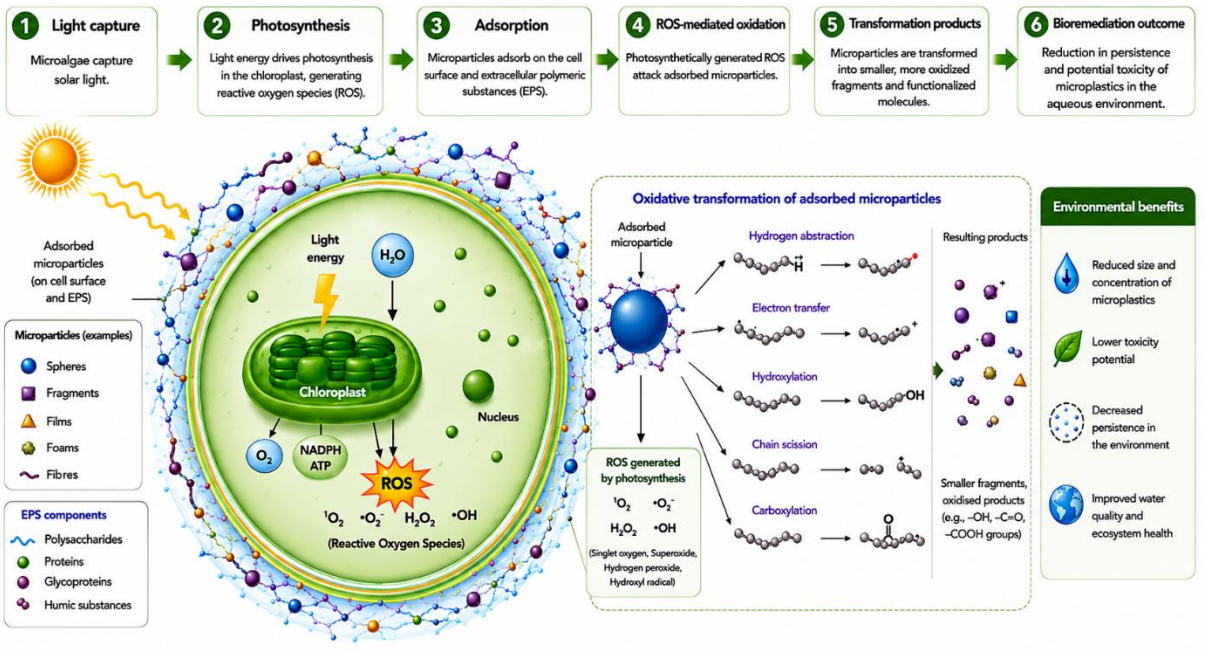

Figure 5. Schematic representation of photobiological oxidation and transformation of microplastics by microalgae.

Table 1. Comparative Analysis of Microalgal Species and their Mechanisms for Microplastic Capture and Removal.

Microalgae species	**Type of microalgae**	**MPS (s)**	**source of microplastic**	**interaction / mechanism**	**Ref.**
Chlorella vulgaris	Green microalga (Chlorophyta)	(PE), (PS), (PP)	Industrial packaging waste, cosmetics, textile industries, domestic wastewater	Strong biosorption through extracellular polymeric substances (EPS); bioflocculation and aggregation of MPs with algal biomass	[24]
Scenedesmus obliquus	Freshwater green microalga	Polystyrene microbeads, PE fragments	Plastic manufacturing effluents, industrial wastewater	Adsorption onto cell surface; formation of hetero-aggregates; oxidative stress-induced transformation of MPs	[25]
Spirulina platensis	Cyanobacterium (blue-green microalga)	(PE), Polyamide fibres	Textile wastewater, cosmetic residues	Bioflocculation and biosorption mediated by polysaccharides and protein-rich cell wall	[26]
Haematococcus pluvialis	Freshwater green microalga	Nanoplastics and PS particles	Industrial plastic degradation products	Surface adsorption and oxidative photobiological transformation under light exposure	[27]
Nannochloropsis oculata	Marine microalga	(PET),PS nanoparticles	Marine industrial discharges and aquaculture activities	EPS-mediated adsorption and sedimentation enhancement	[28]
Dunaliella salina	Halophilic green microalga	PS and PE microplastics	Saline industrial wastewater and desalination rejects	Bioaccumulation of nanosized plastics and antioxidant-mediated stress response	[29]
Chlamydomonas reinhardtii	Unicellular green microalga	Polystyrene nanoplastics	Laboratory and industrial plastic residues	Internalization of nanoplastics, oxidative stress response, partial biodegradation potential	[30]
Skeletonema costatum	Marine diatom	PE and PS particles	Coastal industrial discharge and port / harbour pollution	Adsorption on silica-rich frustules and aggregation with suspended particles	[31]

Factors Affecting Bioremediation Efficiency

Several factors influence the efficiency of microalgae-based bioremediation:

Table 2. Main factors affecting the interaction between microalgae and microplastics during bioremediation.

Factor	Description
Microplastic properties	Size, shape, polymer type, and surface charge influence adsorption and aggregation.[32,33]
Algal species	Microalgae such as Scenedesmus obliquus, Chlorella vulgaris, and Spirulina platensis show variable EPS production, growth rates, and tolerance to microplastics [1,2].
Environmental conditions	Light intensity, temperature, pH, and nutrient availability strongly affect algal growth and interaction with microplastics [2,34].
Exposure time	Sufficient contact time is required to allow adsorption, aggregation, and partial degradation [35].

Industrial Effluents as a Matrix for Bioremediation

Physico-Chemical Complexity of Industrial Wastewaters

Industrial effluents are complex matrices containing microplastics, heavy metals, dyes, surfactants, and nutrients that may influence the effectiveness of microalgae-based bioremediation [36]. Co-contaminants may promote or inhibit microalgal growth and the removal of microplastics. For example, certain heavy metals can cause stress, thereby reducing the photosynthetic efficiency of the algae. Certain nutrients can promote biomass productivity and the release of extracellular polysaccharides (EPS), which may facilitate the adsorption and flocculation of microplastics. Consequently, knowledge of the chemical and physical properties of effluents is essential for selecting suitable algal species and optimizing treatment conditions [38].

Adaptability of Microalgae to Industrial Effluents

Microalgae exhibit varying degrees of tolerance to industrial effluent toxicity, which is critical for successful bioremediation [36]. Some species, such as *Scenedesmus obliquus* and *Chlorella vulgaris*, can survive and grow in high-strength effluents, maintaining their ability to adsorb MPs and produce EPS [37]. Adaptive mechanisms include adjustment of photosynthetic

activity, enhanced EPS secretion, and activation of antioxidant defences to mitigate oxidative stress caused by contaminants [38]. These properties make microalgae versatile candidates for the treatment of diverse industrial effluents [39].

Implications for Bioremediation Performance

The complexity of industrial effluents directly affects the removal efficiency of microplastics [40]. High concentrations of co-contaminants can compete for adsorption sites on algal cells or interfere with bioflocculation processes [41]. Conversely, the presence of nutrients may stimulate algal growth, increase EPS production, and enhance MP aggregation and sedimentation [42]. Pilot studies have demonstrated that tailoring operational parameters—such as dilution, aeration, and residence time—can mitigate inhibitory effects and maximize MP removal [43]. Understanding the matrix-specific challenges is therefore essential for designing scalable microalgae-based wastewater treatment systems.

Experimental Strategies and Technological Approaches

Laboratory-Scale Studies

Laboratory-scale experiments provide controlled conditions to investigate microalgae–microplastic interactions and optimize operational parameters [44]. Batch and continuous cultures are commonly used to evaluate the adsorption, bioflocculation, and partial biodegradation of MPs by different algal species [45]. Variables such as light intensity, temperature, pH, nutrient concentration, and microplastic characteristics are systematically tested to determine the optimal conditions for maximal MP removal [46]. These studies form the foundation for understanding the underlying mechanisms and provide essential data for scaling up to pilot or industrial systems [47].

Pilot and Industrial-Scale Systems

To apply microalgae-based bioremediation on a large scale, pilot and industrial systems are needed. They must maintain good treatment efficiency without making costs explode. Photobioreactors, open ponds, or hybrid systems combining microalgae with filtration or biochar are often used [48]. On a large scale, several difficulties appear: light must be

distributed evenly, nutrient levels must be controlled, enough time must be allowed for microalgae to remove microplastics, and finally, biomass must be harvested efficiently while consuming as little energy as possible [49].

Analytical Methods for Monitoring Microplastic Removal

Accurate monitoring of MP removal is essential [50]. It also helps to characterize algal performance properly. To identify polymers, two techniques are mainly used: Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy. Scanning electron microscopy (SEM) is used to observe surface morphology [51,52]. As for algal biomass and EPS production, they are typically measured through chlorophyll content, dry weight, and various biochemical assays [50,51]. These methods provide both quantitative and qualitative data. They allow researchers to evaluate treatment efficiency and to understand the removal mechanisms.

Advantages, Limitations, and Challenges

Advantages of Microalgae-Based Bioremediation

The use of microalgae in bioremediation can offer several ecological and operational advantages, as it is a sustainable and environmentally friendly technique that helps reduce reliance on chemical treatments [55]. Second, microalgae, having the capacity to remove microplastics and nutrients simultaneously, prevent eutrophication and improve water quality [56]. Third, the generated biomass can be be valorized into biofertilizers, bioenergy, or other bioproducts, thus integrating the process into a circular economy logic [57]. Moreover, microalgae-based systems can adapt to different types of industrial effluents, offering wide versatility along with great scalability.

Limitations

Despite its advantages, microalgae-based bioremediation also has its limits. When there are too many microplastics, or other pollutants such as heavy metals, dyes, or surfactants, the microalgae grow less well. This reduces EPS production and makes the treatment less effective [58]. In general, plastics are never completely degraded. Separating microplastics from algal biomass before valorization also remains difficult. Finally, growing microalgae on a large scale

requires careful control of the surrounding conditions—light, temperature, and pH—as well as fairly intensive operational management to maintain good performance [59].

Challenges and Research Gaps

Major challenges to implementing microalgae-based systems at the industrial scale include standardizing protocols for MP removal, developing reliable monitoring methods, and assessing the long-term ecotoxicological effects of MPs on algal populations [60]. Further research is needed to optimize species selection, improve biomass harvesting techniques, enhance MP adsorption and flocculation, and evaluate the feasibility of integrating these systems into existing wastewater treatment infrastructure [61]. These gaps must be bridged before successful laboratory studies can be translated into industrial use.

Conclusion

Bioremediation based on the use of microalgae is a promising, cost-effective, and sustainable method for treating industrial effluents contaminated by small microplastic particles. Thanks to several mechanisms, such as adsorption, bioflocculation, and partial degradation, microalgae manage to reduce the amount of microplastics present in effluents, while retaining the ability to capture nutrients and produce biomass that can be reused. Laboratory studies have shown that several species, such as *Scenedesmus obliquus*, *Chlorella vulgaris*, and *Spirulina platensis*, can have this property of adaptation to complex industrial effluents and remain effective even when experimental conditions change. Challenges still remain to be understood and resolved, such as the incomplete degradation of polymers, the negative effects of other pollutants present in the effluent, and the difficulty of separating these MP aggregates from the algal biomass before valorizing it. Future research should focus more on the choice of the best algal species used, the combination of microalgae with other biotechnologies, the creation of standardized experimental protocols, and the study of feasibility at the industrial scale. By following all these principles of the circular economy and sustainability policy, new efficient, eco-friendly, and, of course, cost-effective solutions could thus be implemented to reduce this pollution by these dangerous microparticles in industrial effluents. Future research should prioritize the integration of microalgae with complementary biotechnologies, such as bacterial consortia, enzymes, or biofilms, to enhance microplastic removal efficiency and overall treatment

performance. Additionally, adopting circular economy approaches through biomass valorization (biofertilizers, bioenergy, or bioproducts), standardizing experimental protocols, and implementing life cycle and techno-economic assessments will be essential to promote sustainable industrial applications. By addressing these challenges, microalgae-based bioremediation can be developed into a reliable and eco-friendly solution for mitigating microplastic pollution in industrial effluents.

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Ethics Approval
Not applicable. This review article did not include human participants, animals, or clinical data

Data Availability
No datasets were generated or analysed during the current study.

Code Availability
Not applicable. No code or software was developed or analysed during this study.

Conflict of Interest
The authors declare that they have no conflict of interest.

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